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Study of the $X(3872)$ and $Y(4260)$ in $B^0 \to J/\psi\pi^+\pi^-K^0$ and $B^- \to J/\psi\pi^+\pi^-K^-$ decays

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We present results of a search for the $X(3872)$ in $B^0 \to X(3872)K^0_S$, $X(3872) \to J/\psi\pi^+\pi^-$, improved measurements of $B^- \to X(3872)K^-$, and a study of the $J/\psi\pi^+\pi^-$ mass region above the $X(3872)$. We use 232×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II e^+e^- asymmetric-energy storage rings. The results include the 90% confidence interval $1.34 \times 10^{-6} < \mathcal{B}(B^0 \to X(3872)K^0, X \to J/\psi\pi^+\pi^-) < 10.3 \times 10^{-6}$ and the branching fraction $\mathcal{B}(B^- \to X(3872)K^-, X \to J/\psi\pi^+\pi^-) = (10.1 \pm 2.5 \pm 1.0) \times 10^{-6}$. We observe a $(2.7 \pm 1.3 \pm 0.2)\mathrm{MeV}/c^2$ mass difference of the $X(3872)$ produced in the two decay modes. Furthermore, we search for the $Y(4260)$ in B decays and set the 95% C.L. upper limit $\mathcal{B}(B^- \to Y(4260)K^-, Y(4260) \to J/\psi\pi^+\pi^-) < 2.9 \times 10^{-5}$.

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The $X(3872)$ was first observed in the charged B-meson decay [1] $B^- \to X(3872)K^-$, $X(3872) \to J/\psi\pi^+\pi^-$ by the Belle Collaboration [2]. It has been confirmed by the *BABAR* Collaboration [3] and observed inclusively in the same final state by the CDF and D0 collaborations [4]. This narrow-width particle has a mass very near the $D^0\bar{D}^{*0}$ threshold and decays into final states containing charmonium (J/ψ). The most plausible interpretation [5] was a 1^3D_2 or 1^1D_2 $c\bar{c}$ state which would be narrow since it would be forbidden to decay into open charm $D\bar{D}$ states. However, these candidates should have large radiative transitions into χ_c states that have not been observed [2]. Recent studies from Belle that combine angular and kinematic properties of the $\pi^+\pi^-$ mass, strongly favor a $J^{PC} = 1^{++}$ state [6]. Other explanations include 2^1P_1 $c\bar{c}$ (1^{+-}) or 2^3P_1 1^{++} states that should be narrow, but are predicted to be about 100 MeV$/c^2$ higher than the $X(3872)$ mass and are not expected to have a large decay rate into $J/\psi\pi\pi$ final states [7]. Hence, the $X(3872)$ appears not to be a simple quark model $q\bar{q}$ meson state.

Many explanations have been proposed for the nature of the $X(3872)$. Recent interpretations include the diquark-antidiquark model [8] and the S-wave $D^0\bar{D}^{*0}$ molecule model [9]. The diquark-antidiquark model predicts a spectrum of $J = 0, 1, 2$ particles and identifies the $X(3872)$ as its 1^{++} member state with the two quark combinations $X_u = [cu][\bar{c}\,\bar{u}]$ and $X_d = [cd][\bar{c}\,\bar{d}]$ with a mass difference $m(X_d) - m(X_u) \approx (7 \pm 2)\mathrm{MeV}/c^2$. In addition, these two states could form mixed states that are produced in both charged and neutral B-meson decays with different masses and rates depending on the mixing angle. A search for the predicted charged partner of the $X(3872)$ has been addressed in a previous analysis with an upper limit that is still consistent with the model [10]. The $D^0\bar{D}^{*0}$ molecule model interprets the $X(3872)$ as a loosely bound $D^0\bar{D}^{*0}$ S-wave state that is produced in weak decays of the B-meson into $D^0\bar{D}^{*0}K$. In this picture, the S-wave molecule must form a $J^P = 1^+$ state. From factorization, heavy-quark symmetry, and isospin symmetry, the decay $B^0 \to X(3872)K^0$ is predicted to be suppressed by an order of magnitude relative to $B^- \to X(3872)K^-$ [9]. To investigate these predictions, we present in this letter a study of the neutral mode $B^0 \to X(3872)K^0$, $X(3872) \to J/\psi\pi^+\pi^-$ and we analyze $B^- \to J/\psi\pi^+\pi^-K^-$ decays with increased statistics to obtain improved measurements of $X(3872) \to J/\psi\pi^+\pi^-$. In addition, we examine the higher $J/\psi\pi^+\pi^-$ invariant mass region to search for a structure recently observed in initial state radiation (ISR) events [11].

The data were collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings on the $\Upsilon(4S)$ resonance. The integrated luminosity of the data used in this analysis is $211\mathrm{fb}^{-1}$; this corresponds to the production of $(232 \pm 3) \times 10^6$ $B\bar{B}$ pairs.

The *BABAR* detector is described in detail elsewhere [12]. Charged-particle trajectories are measured by a combination of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) in a 1.5-T solenoidal magnetic field. For charged-particle identification, we combine information from a ring-imaging Cherenkov detector (DIRC) and energy-loss measurements provided by the SVT and the DCH. Photons and electrons are detected in a CsI(Tl) electromagnetic calorimeter (EMC). Penetrating muons are identified by resistive-plate chambers in the instrumented magnetic flux return (IFR).

Charged pion candidates are required to be detected in at least 12 DCH layers and have a transverse momentum greater than 100 MeV$/c$. Kaons, electrons, and muons are separated from pions based on information from the IFR and DIRC, energy loss in the SVT and DCH (dE/dx), or the ratio of the candidate EMC energy deposition to its momentum (E/p). Photon candidates are identified with clusters in the EMC with total energy >30 MeV and a shower shape consistent with that expected from a photon.

The $B^0 \to J/\psi\pi^+\pi^-K^0_S$ and $B^- \to J/\psi\pi^+\pi^-K^-$ decays are reconstructed in the following way. Electron candidates and bremsstrahlung photons satisfying $2.95 < m(e^+e^-(\gamma)) < 3.14\ \mathrm{GeV}/c^2$ are used to form $J/\psi \to e^+e^-$ candidates. A pair of muon candidates within the mass interval $3.06 < m(\mu^+\mu^-) < 3.14\ \mathrm{GeV}/c^2$ is required for a $J/\psi \to \mu^+\mu^-$ candidate. A mass constraint to the nominal J/ψ mass [13] is imposed in the fit of the lepton pairs. We reconstruct $K^0_S \to \pi^+\pi^-$ candidates from pairs of oppositely charged tracks forming a vertex with a χ^2 probability larger than 0.1%, a flight-length significance $l/\sigma(l) > 3$ and an invariant mass within 15 MeV$/c^2$ of the nominal K^0_S mass [13]. $X(3872)$ candidates are formed by combining J/ψ candidates with two oppositely charged pion candidates fitted to a common vertex. Finally, we form $B^0(B^-)$ candidates by combining $X(3872)$ candidates with $K^0_S(K^-)$ candidates. To suppress continuum background, we select only events with a ratio of the second to the zeroth Fox-Wolfram moment [14] less than 0.5.

We use two kinematic variables to identify signal events from B decays: the difference between the energy of the B candidate and the beam energy, $\Delta\mathrm{E} \equiv E^*_B - \sqrt{s}/2$, and the energy-substituted mass $\mathrm{m_{ES}} \equiv \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$. Here $(E_i, \mathbf{p}_i)$ is the four-vector (in the laboratory frame) and $\sqrt{s}$ is the center-of-mass (CM) energy of the e^+e^- system. E^*_B is the energy of the B candidate in the CM system and $\mathbf{p}_B$ the momentum in the laboratory frame. The signature of signal events is $\Delta E \approx 0$, and $\mathrm{m_{ES}} \approx m_B$ where m_B is the mass of the B-meson [13].

We optimize the signal selection criteria by maximizing the ratio $n_s^{\mathrm{MC}}/(3/2 + \sqrt{n_b^{\mathrm{MC}}})$ [15] where n_s^{MC} (n_b^{MC}) are the number of reconstructed Monte Carlo (MC) signal (background) events. The optimization was performed by varying the selection criteria on ΔE, m_{ES}, the candidate masses of the $X(3872)$ and K^0_S, and the particle identification (PID) requirements of leptons, pions, and charged kaons. The criteria $|\Delta\mathrm{E}| < 15$ MeV, $|\mathrm{m_{ES}} - m_B| < 6$ MeV$/c^2$ and $|m(J/\psi\pi^+\pi^-) - 3872\ \mathrm{MeV}/c^2| < 6$ MeV$/c^2$ (signal region) were found to be optimal for selecting signal events. In case of multiple candidates in an event, we select the candidate with the smallest value of $|\Delta\mathrm{E}|$. Applying our optimized selection criteria, we compute the $J/\psi\pi^+\pi^-$ invariant mass in the range $3.8 - 3.95$ GeV$/c^2$ shown in Figs. 1(a) and 1(b) for the B^- and B^0 mode, respectively. The shaded area shows events in the sideband region $|\mathrm{m_{ES}} - 5260| < 6$ MeV$/c^2$.

We extract the number of signal events with an extended unbinned maximum-likelihood fit to the two-dimensional distribution $y(\mathrm{m_{ES}}, m_X)$ where m_X is the $J/\psi\pi^+\pi^-$ invariant mass. The probability density function (PDF) (normalized to the total number of events) is $\mathcal{P}(y) = \sum_t n_t \mathcal{P}_t(y)$ where n_t is the number of events of category t. We consider three different event categories: signal, B decays with the same final-state particles as the signal that accumulate near $\mathrm{m_{ES}} \approx m_B$ (peaking background), and combinatorial background. The individual PDFs $\mathcal{P}_t$ are assumed to be uncorrelated in $m_{\mathrm{ES}}$and m_X and can therefore be factorized as $\mathcal{P}_t(y) = g_t(\mathrm{m_{ES}})h_t(m_X)$, where g_t and h_t represent the $\mathrm{m_{ES}}$ and m_X probability distributions, respectively. The $B \to X(3872)K$ signal events are modeled by a Gaussian distribution in m_{ES}. The resolution function in m_X for those events is best described by a Cauchy function [16] due to the mass constraint of the J/ψcandidate. The PDF for peaking background events is parameterized by a Gaussian distribution in m_{ES} and a linear function in m_X. We model combinatorial background events by an ARGUS function [17] in m_{ES} and a linear function in m_X. The fit performance was validated with MC experiments. The mean and width of the m_{ES} Gaussian distribution for signal and peaking background and the width of the m_X Cauchy distribution for the B^0 mode were fixed to values obtained from MC samples. Other parameters are allowed to vary in the fit.

The fit is performed in the region $5.2 < \mathrm{m_{ES}} < 5.3$ GeV$/c^2$ and $3.80 < m_X < 3.95$ GeV$/c^2$ without applying the optimized selection criteria on those two variables. The signal region projections of the two-dimensional fit are shown in Fig. 1 for the B^- (a,c) and B^0 (b,d) modes. We obtain 61.2 ± 15.3 signal events for the B^- mode (n_s^-) and 8.3 ± 4.5 signal events for the B^0 mode (n_s^0), respectively. In the following we interpret the observed events in the B^0 mode as the $X(3872)$.

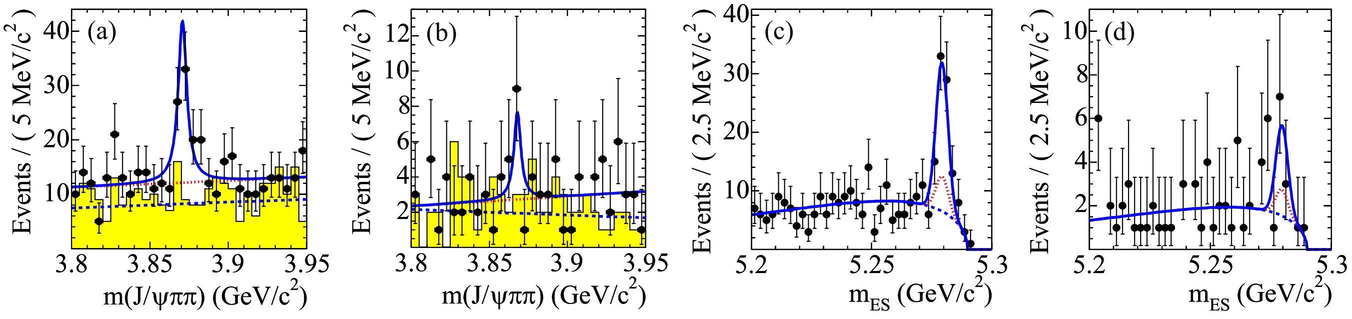

FIG. 1 (color online). Signal region projections of $m(J/\psi\pi^+\pi^-)$ and m_{ES} for $B^- \to X(3872)K^-$ (a,c) and $B^0 \to X(3872)K^0_S$ (b,d). The dashed line represents the combinatorial background PDF, the dotted line represents the sum of the combinatorial and peaking background PDF, and the solid line the sum of all background plus the signal PDF. The shaded area shows events in the m_{ES} sideband region $|\mathrm{m_{ES}} - 5260\ \mathrm{MeV}/c^2| < 6$ MeV$/c^2$.

The efficiency is determined from MC samples with an $X(3872)$ signal of zero width at $3.872\ \mathrm{GeV}/c^2$. The decay model consists of the sequential isotropic decays $B \to X(3872)K$, $X(3872) \to J/\psi\rho^0$, and $\rho^0 \to \pi^+\pi^-$. Compared to a three-body decay, this gives a more accurate description of the observed $\pi^+\pi^-$ invariant mass distribution [3]. Efficiencies are corrected for the small differences in PID and tracking efficiencies that are found by comparing data and MC control samples. The final efficiencies are $(17.4 \pm 0.2)\%$ for the B^0/K^0_Smode and $(22.2 \pm 0.2)\%$ for the B^-/K^-mode.

The branching fraction systematic errors (B^-, B^0 mode in %) include uncertainties in the number of $B\overline{B}$ events (1.1, 1.1), secondary branching fractions (5.0, 5.0) [13], efficiency calculation due to limited MC statistics (0.7, 1.9), MC decay model of the $X(3872)$(1.0, 1.6), differences between data and MC (1.8, 8.9), PID (5.0, 5.0), charged-particle tracking (6.0, 4.8), and K^0_S reconstruction (− , 1.6). The production ratio of B^0 and B^- mesons in $\Upsilon(4S)$ decays is 1.006 ± 0.048 [18]. The total fractional error obtained by adding the uncertainties in quadrature is 9.6% and 12.8% for the B^- and B^0 mode, respectively.

Assuming Gaussian systematic errors with a PDF $P_{sys}(n) \sim \exp[-(n - n_S)^2/2\sigma^2_{sys}]$, the negative log-likelihood (NLL) function including systematic errors is $L_{sys} = ([1/L(n)] - [1/\ln P_{sys}(n)])^{-1}$ where $L(n) = -\ln(\mathcal{L}(n)/\mathcal{L}_{\max})$ is the NLL projection of the parameter estimate n of the number of signal events and σ_{sys} is the systematic error on the number of signal events. The significance including systematic errors obtained from $\sqrt{2L_{sys}(n=0)}$ is 2.5σ for the B^0 mode and 6.1σ for the B^- mode. The statistical significance ($\sigma_{sys} = 0$) of the signal is 2.6σ and 7.5σ, respectively.

Using n^0_S and n^-_S, the efficiencies, the secondary branching fractions and the number of $B\overline{B}$ events, we obtain the branching fractions $\mathcal{B}^0 \equiv \mathcal{B}(B^0 \to X(3872)K^0, X \to J/\psi\pi^+\pi^-) = (5.1 \pm 2.8 \pm 0.7) \times 10^{-6}$ and $\mathcal{B}^- \equiv \mathcal{B}(B^- \to X(3872)K^-, X \to J/\psi\pi^+\pi^-) = (10.1 \pm 2.5 \pm 1.0) \times 10^{-6}$. For the ratio of branching fractions, $R \equiv \mathcal{B}^0/\mathcal{B}^-$, where most of the systematic errors cancel, we obtain $R = 0.50 \pm 0.30 \pm 0.05$. We calculate a 90% confidence level (C.L.) likelihood interval [19] $[n_l, n_h]$ for the number of signal events in the B^0 mode by solving the equation $2L_{sys}(n_{l,h}) = [\mathrm{erf}^{-1}(0.95)]^2$. With $n_l = 2.2$ and $n_h = 16.9$ the 90% C.L. interval on $\mathcal{B}^0$ is $1.34 \times 10^{-6} < \mathcal{B}^0 < 10.3 \times 10^{-6}$. Using the same strategy, the confidence interval on the ratio of branching fractions becomes $0.13 < R < 1.10$ at 90% C.L.

We measure the mass of the $X(3872)$in both modes in reference to the precisely measured $\psi(2S)$ mass [13]. We fit the $J/\psi\pi^+\pi^-$ invariant mass in the $\psi(2S)$ and $X(3872)$ region and calculate $m_X = m_{X,\mathrm{fit}} - m_{\psi(2S),\mathrm{fit}} + m_{\psi(2S)}$. The result for the B^0 mode is $(3868.6 \pm 1.2 \pm 0.2)\mathrm{MeV}/c^2$ and $(3871.3 \pm 0.6 \pm 0.1)\mathrm{MeV}/c^2$ for the B^-mode, where the first error is the statistical uncertainty on $m_{X,\mathrm{fit}}$ and the second is the uncertainty on $m_{\psi(2S),\mathrm{fit}}$ and $m_{\psi(2S)}$ [13]. The mass difference of the $X(3872)$ produced in B^0 and B^- decays is $\Delta m = (2.7 \pm 1.3 \pm 0.2)\mathrm{MeV}/c^2$. The full width at half maximum of the X-mass distribution from the fit on data is $(6.7 \pm 2.7)\mathrm{MeV}/c^2$, which is consistent with the MC-determined value of $(5.4 \pm 0.1)\mathrm{MeV}/c^2$. From this we calculate the 90% C.L. upper limit on the natural width as $\Gamma < 4.1\ \mathrm{MeV}/c^2$.

Recent observations by *BABAR* [11] in ISR events provide evidence for at least one broad resonance in the invariant mass spectrum of $J/\psi\pi^+\pi^-$ at $4.259\ \mathrm{GeV}/c^2$ that can be characterized by a single resonance with a full width of $88\ \mathrm{MeV}/c^2$. This structure is referred to as $Y(4260)$. We search in B^- decays for states decaying into $J/\psi\pi^+\pi^-$ above $4\ \mathrm{GeV}/c^2$ and impose the additional selection criterion $|m(K^-\pi^+\pi^-) - 1273\ \mathrm{MeV}/c^2| > 250\ \mathrm{MeV}/c^2$, which removes backgrounds from $K_1(1270)$ decays. In the resulting mass distribution, Fig. 2, we observe large combinatoric backgrounds and cannot reliably determine the parameters of one or more resonances. We use a two-dimensional PDF identical to the previous model, but fix the central value and width of the signal component to the ISR results [11]. The natural width of $88\ \mathrm{MeV}/c^2$ has been enlarged by the detector resolution, which is found to be the same as for the mass region around $3.87\ \mathrm{GeV}/c^2$. The m_X projection of the two-dimensional fit is overlaid in Fig. 2 and yields 128 ± 42 signal events. The statistical significance calculated from $\sqrt{-2\ln\mathcal{L}_0/\mathcal{L}}$ is 3.1σ where $\mathcal{L}$ and $\mathcal{L}_0$ are the maximum likelihood of the fit and the null hypothesis fit, respectively. Using a phase-space MC simulation of a state at $4.26\ \mathrm{GeV}/c^2$ decaying into $J/\psi\pi^+\pi^-$ and assuming the same systematic uncertainties and efficiency corrections as for the $X(3872)$, we obtain the 95% C.L. upper limit on the

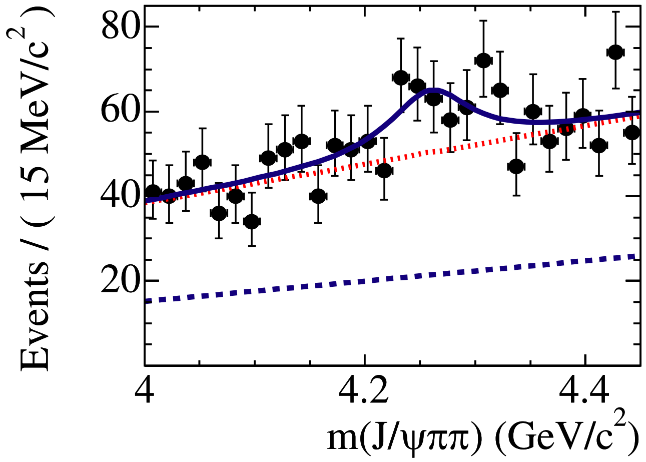

FIG. 2 (color online). Projection of the two-dimensional fit for the mass region above $4\ \mathrm{GeV}/c^2$ for events within the m_{ES} signal region in $B^- \to J/\psi\pi^+\pi^-K^-$. The lines represent the same event types as in Fig. 1.

branching fraction $\mathcal{B}_Y = \mathcal{B}(B^- \to Y(4260)K^-, Y(4260) \to J/\psi\pi^+\pi^-) < 2.9 \times 10^{-5}$. The 90% C.L. likelihood interval on the branching fraction $\mathcal{B}_Y = (2.0 \pm 0.7 \pm 0.2) \times 10^{-5}$ is $1.2 \times 10^{-5} < \mathcal{B}_Y < 2.9 \times 10^{-5}$.

In conclusion, our studies of the $J/\psi\pi^+\pi^-$ invariant mass below 4 GeV$/c^2$ yield a signal of 2.5σ and 6.1σ significance in the B^0 and B^- mode, respectively, with a ratio of branching fractions $R = 0.50 \pm 0.30 \pm 0.05$. We observe an excess of events above background in the $J/\psi\pi^+\pi^-$ invariant mass between 4.2 and 4.4 GeV$/c^2$. These events are consistent with the broad structure observed in ISR events [11].

If one narrow state is observed in the mode $B^- \to X(3872)K^-$, $X \to J/\psi\pi^+\pi^-$, the diquark-antidiquark model [8] predicts one amplitude (from X_d or X_u) to be dominant in the charged mode and the other amplitude to be dominant in the neutral mode. In this case, the model predicts the relative rates to be equal ($R = 1$) and the mass difference to be (7 ± 2)MeV$/c^2$. The ratio of branching fractions is consistent with our measurement, $0.13 < R < 1.10$ at 90% C.L., and the observed mass difference of $(2.7 \pm 1.3 \pm 0.2)$MeV$/c^2$ is both consistent with zero and the model prediction within 2 standard deviations. In the S-wave molecule model [9], the neutral mode branching fraction is predicted to be at least 10 times smaller ($R < 0.1$) than the charged mode. However, we obtain a ratio of neutral to charged branching fractions which is slightly more consistent with isospin-conserving decays.

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